Hydraulic Fracturing Processes in the Laboratory

Bruno Gonçalves da Silva

PhD Candidate,
Department of Civil and Environmental Engineering

In collaboration with Professor Einstein

MIT Earth Resources Laboratory
2016 Annual Founding Members Meeting
May 18, 2016

Earth Resources Laboratory

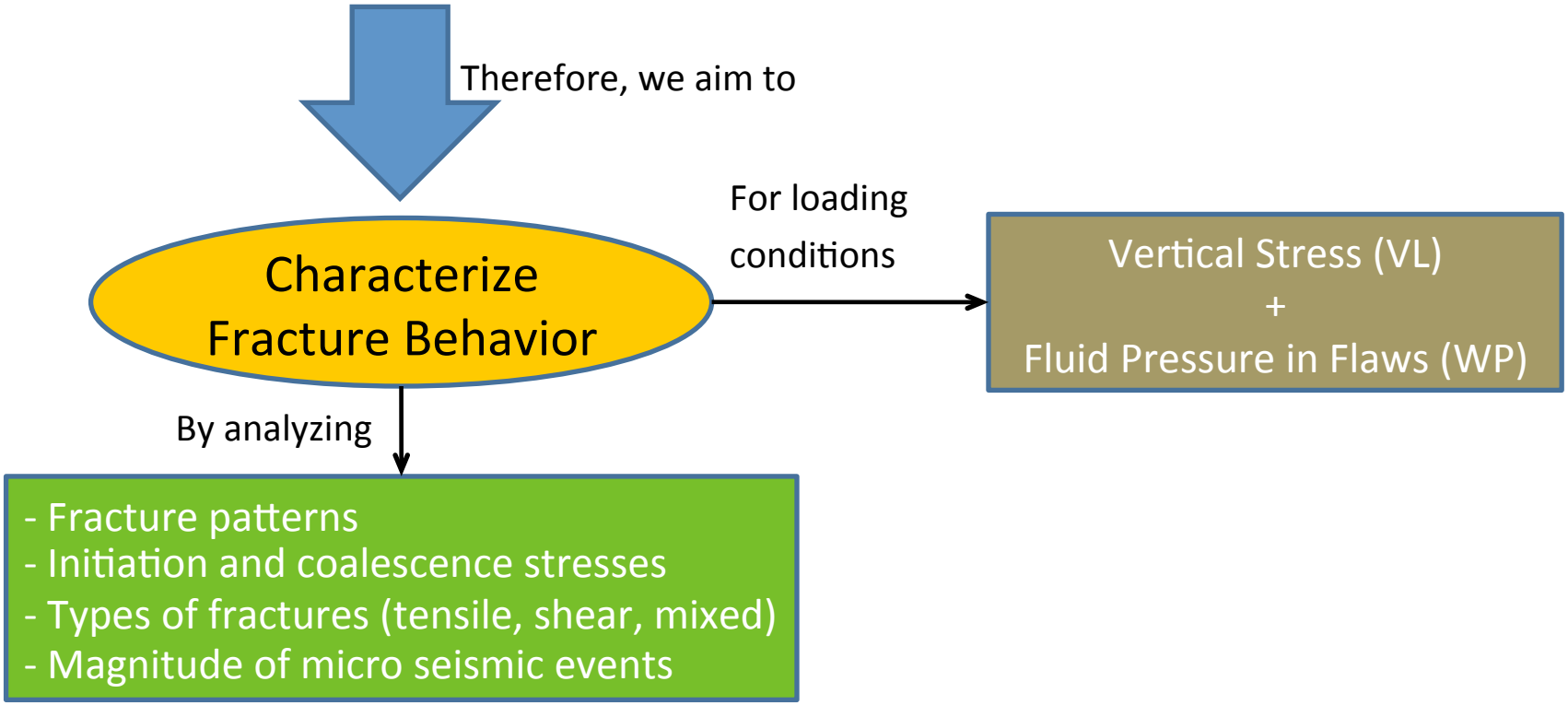
Massachusetts Institute of Technology

Outline

- Motivation
- Objectives
- Experimental Activities
  - Specimen and flaw geometries
  - Test setup
  - Major results
- Source Mechanism of Fracturing Events
- Conclusions

Motivation

- What fracturing processes occur when a rock is hydraulically fractured?



Objectives

Vertical Stress (VL)
+
Fluid Pressure in Flaws (WP)

FRACTURING PROCESSES

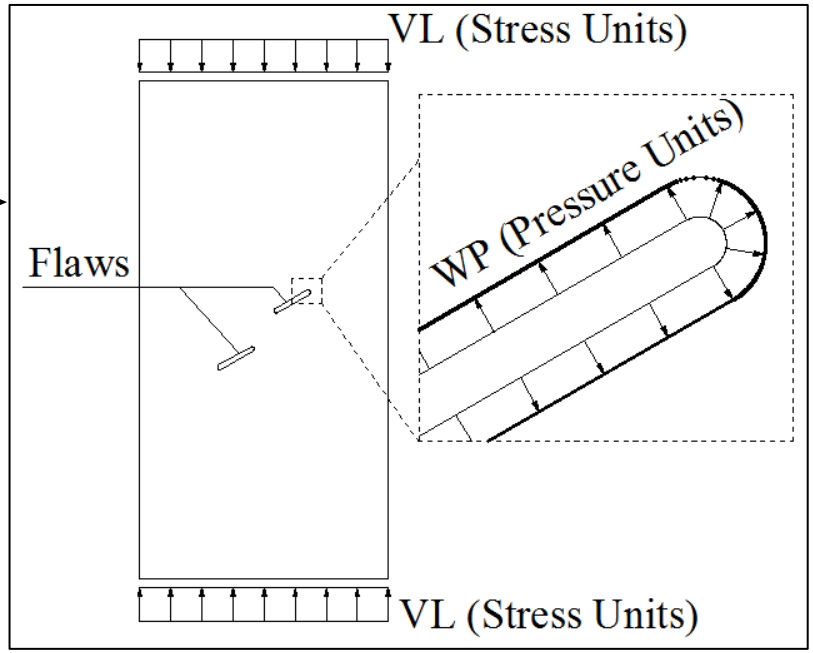
Visually

Compare

Acoustic Emissions

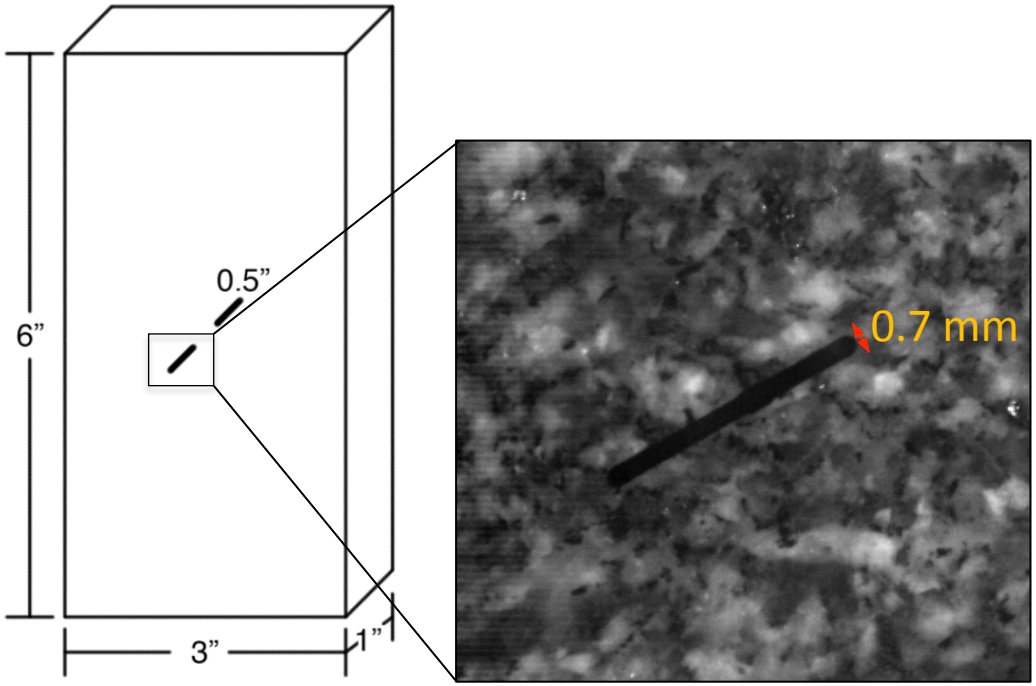
High-Speed Video
Last seconds of test

High-Resolution Images
Every 2 sec throughout test

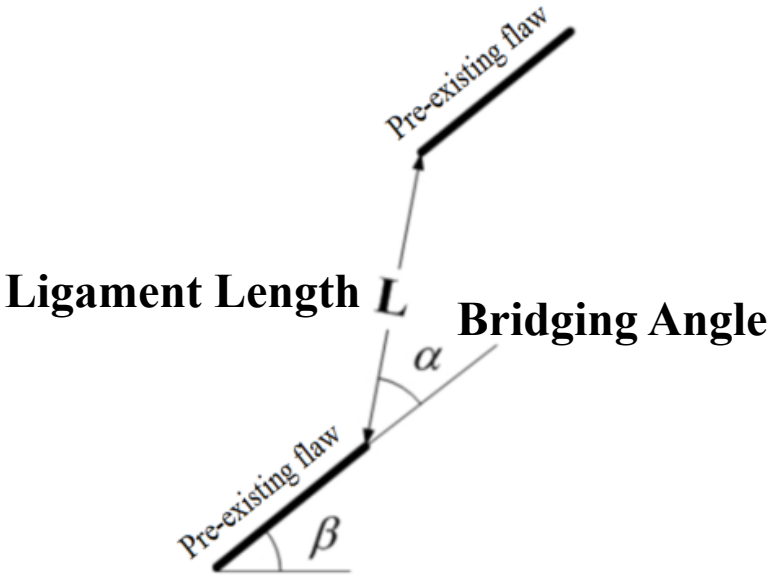


Experimental Activities

Specimen and Double Flaw Geometries



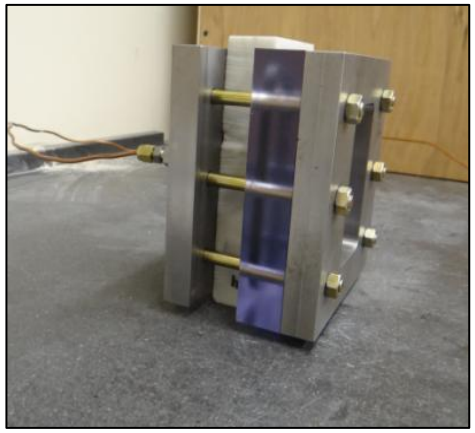
Granite Specimen

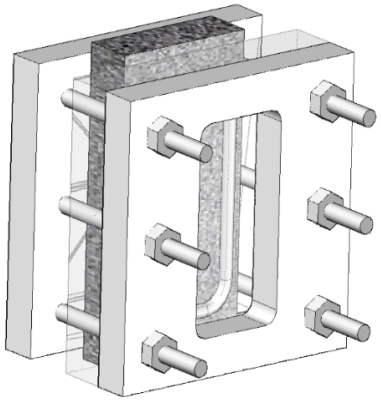


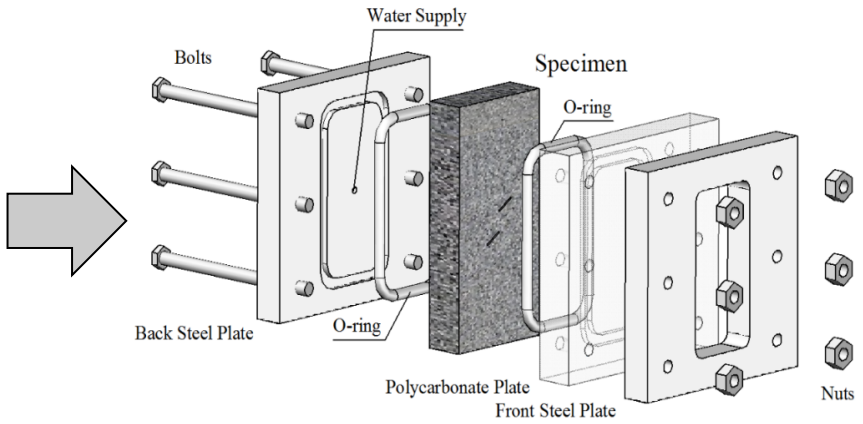
L-β-α

Experimental Activities

Equipment Developed – designed and built at MIT



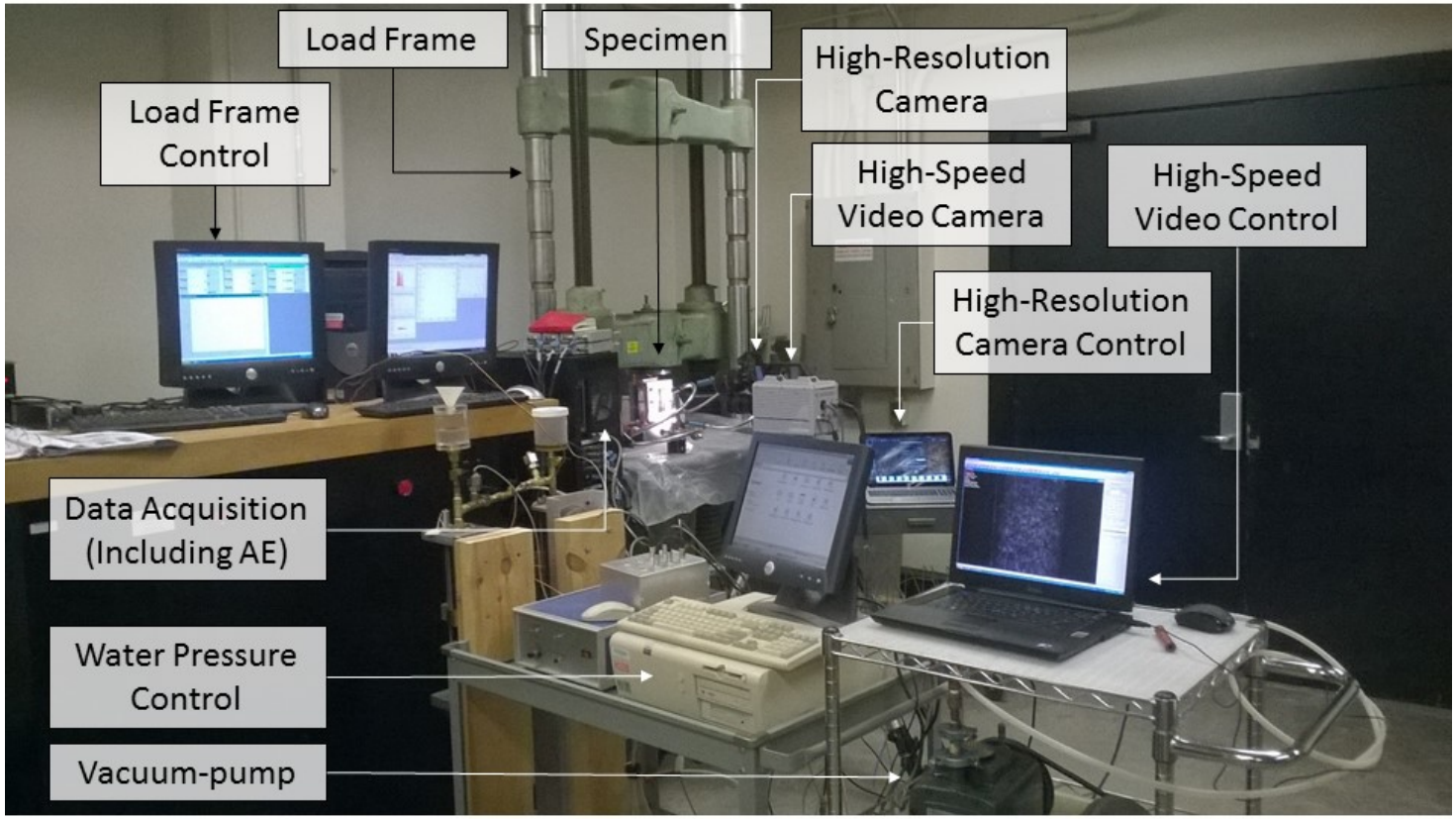




- Designed to withstand 10MPa of water pressure

Experimental Activities

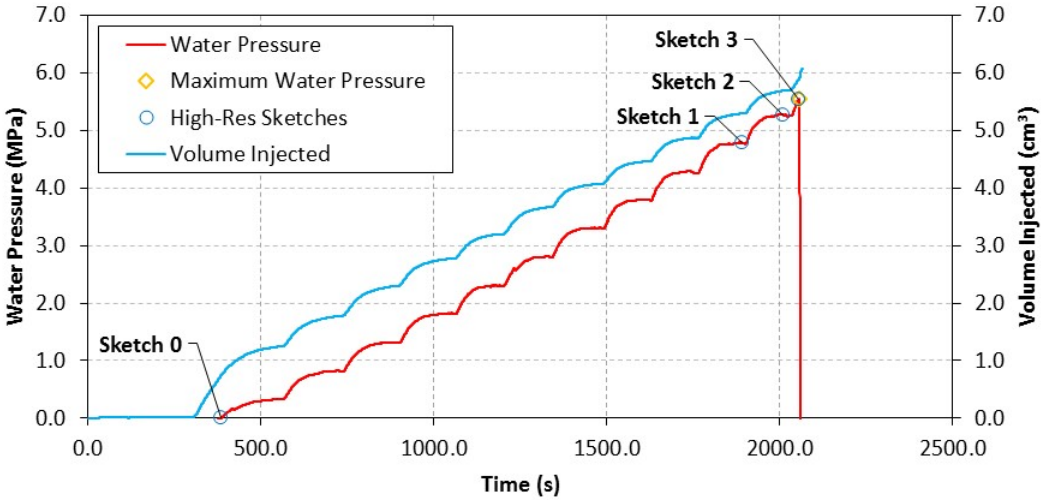
Test Setup



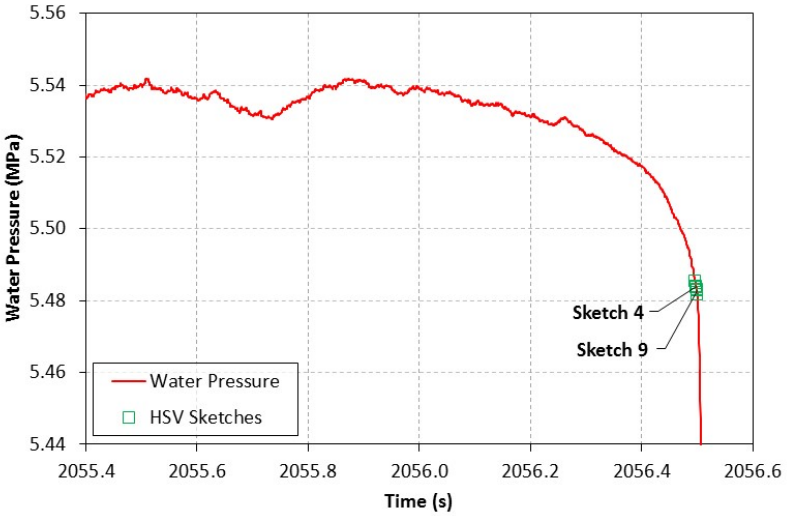
Experimental Activities

Example of data obtained from a test

Test on geometry 2a-30-90 (Vertical Load – 5MPa)



WP and Volume Injected vs Time
for the entire test



WP and Volume Injected vs Time
for the last 1.2 seconds of the test

Experimental Activities

Example of imaging data obtained from a test

High-Res Frame: Initial

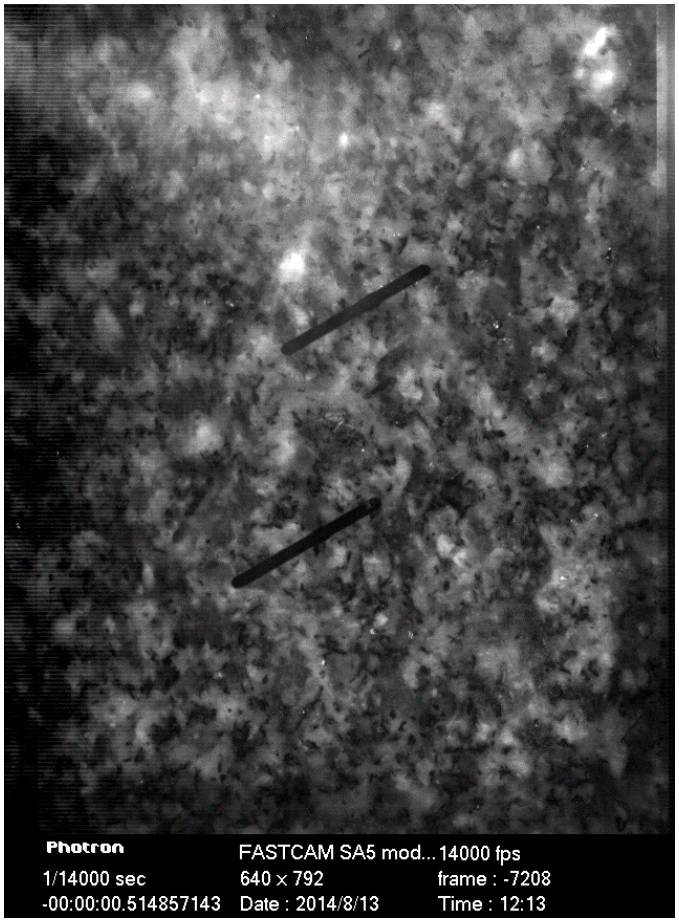
p_{water}: 0.01 MPa

$\sigma_{vertical}$: 5.00 MPa

HSV Frame: Final (at failure)

p_{water}: -0.15 MPa

$\sigma_{vertical}$: 5.00 MPa



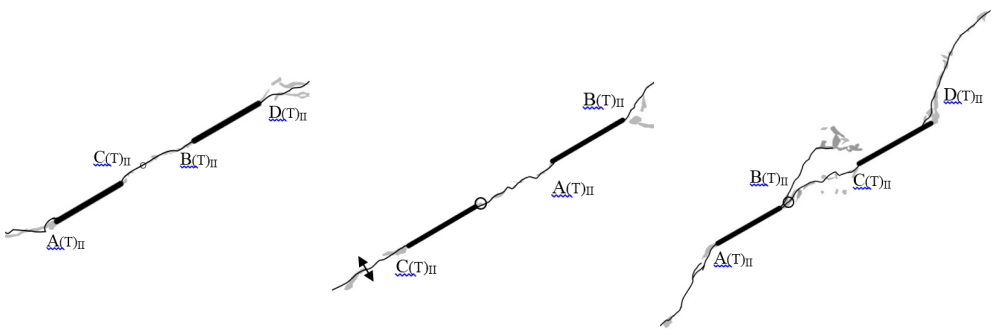
- High-resolution images captured every 5 or 2 seconds throughout the tests
- High-Speed Video (HSV) Frames capturing approximately last 1.6 sec of the tests

Experimental Activities

Example of fracturing patterns for one geometry

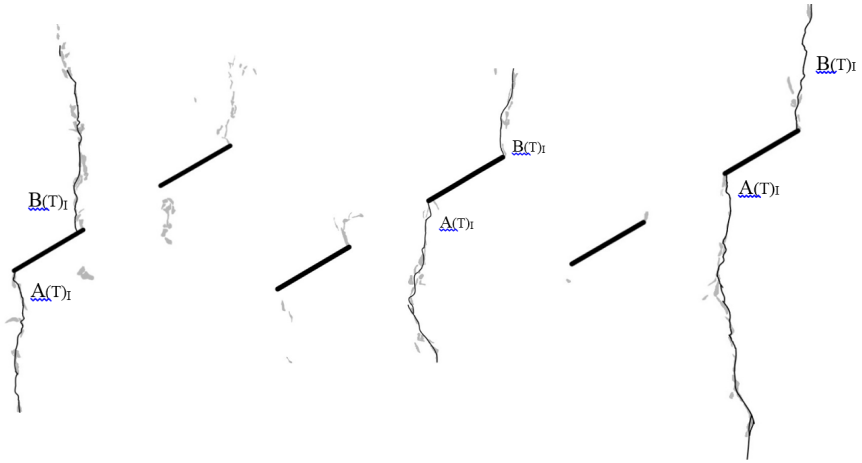
Example: Gr-2a-30-0

VL = 0 MPa



Coalescence
Direct Category 6

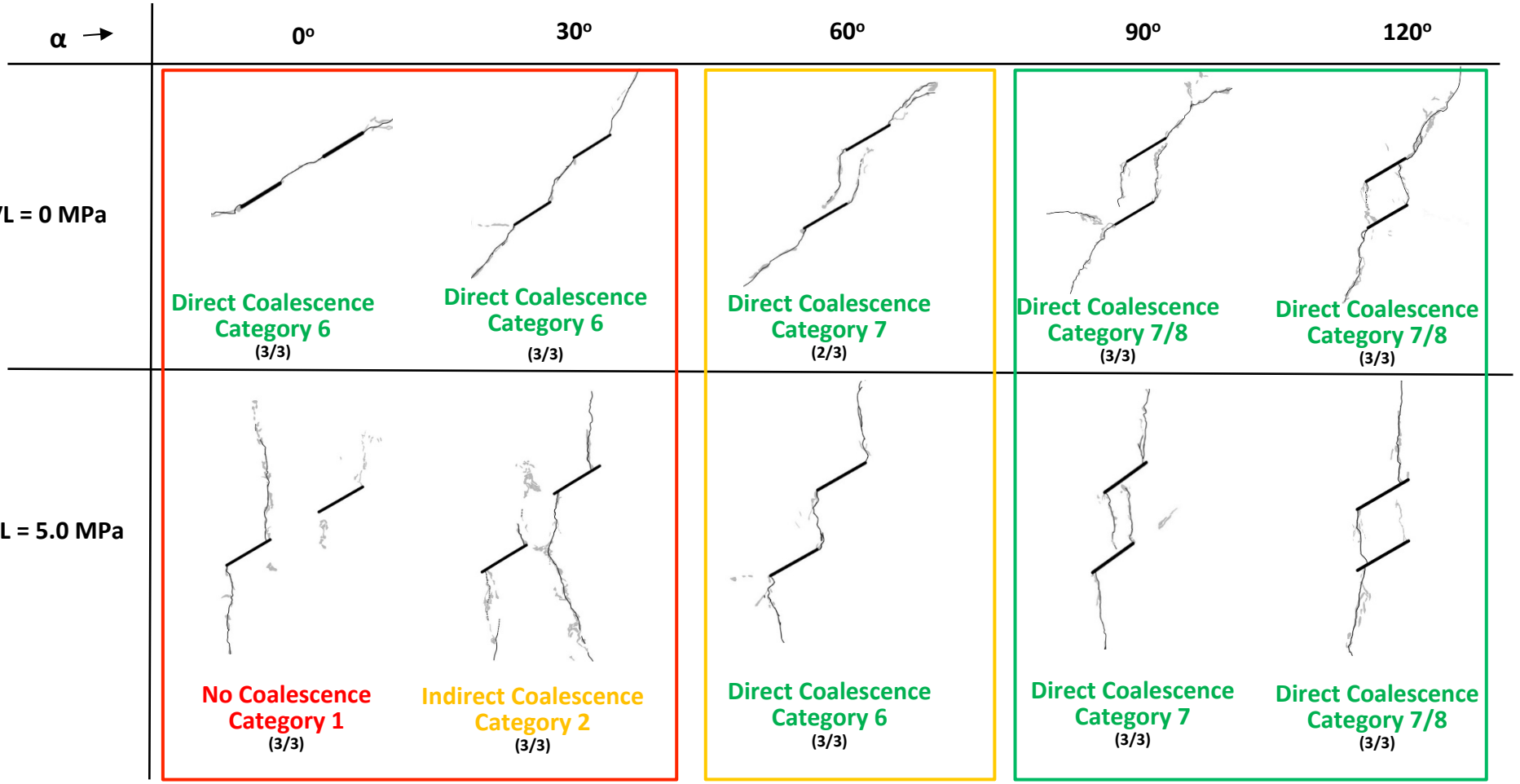
VL = 5.0 MPa



No Coalescence
Category 1

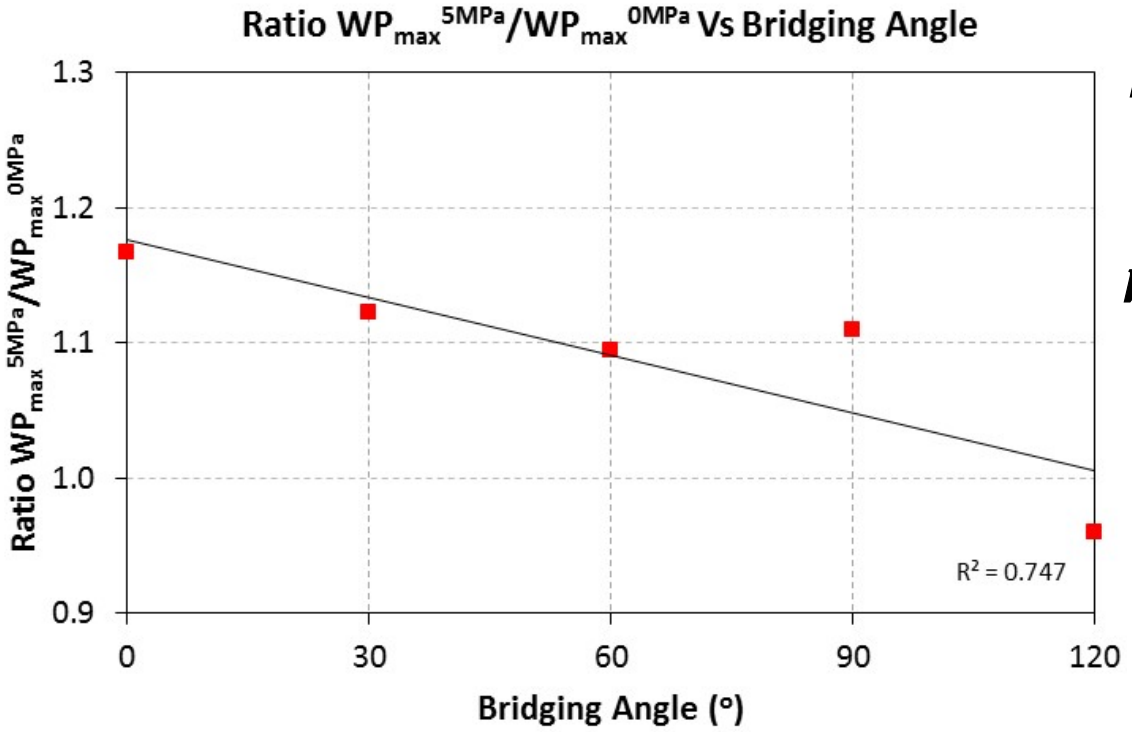
Experimental Activities

Summary of coalescence patterns – 2a-30-α



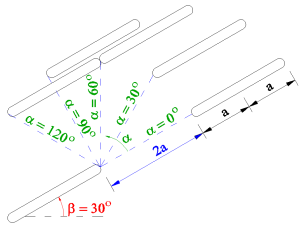
Experimental Activities

Maximum Water Pressure vs Bridging Angle α



$WP_{max}(0MPa)$ – average maximum water pressure reached when the specimens of a given are subject to a vertical stress of 0 MPa

$WP_{max}(5MPa)$ – average maximum water pressure reached when the specimens of a given geometry are subject to a vertical stress of 5 MPa



- The ratio between the maximum water pressures at 5MPa and 0MPa appears to decrease as the bridging angle increases

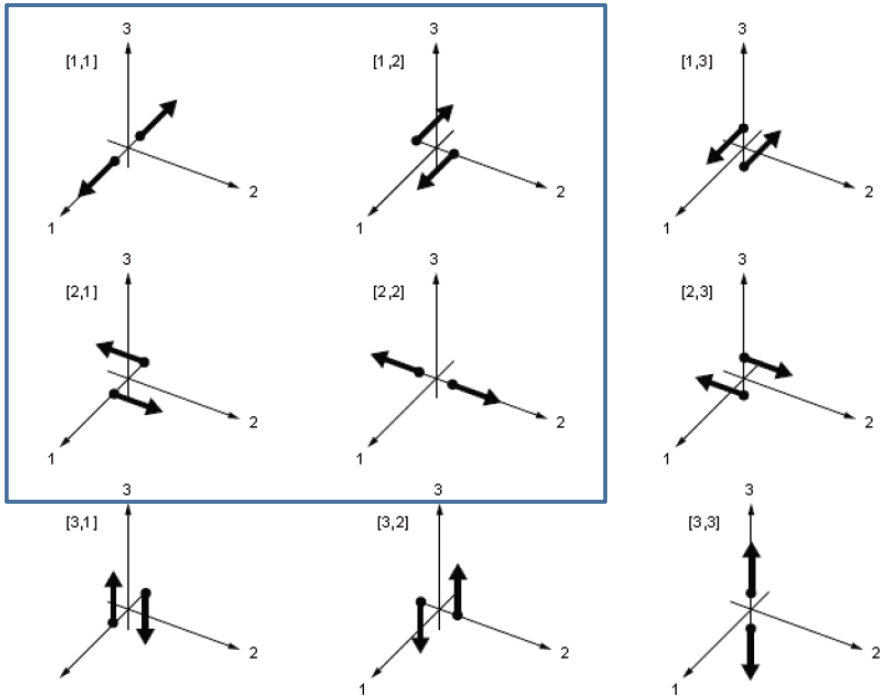
Source Mechanism of Fracturing Events

Methodology

- Produce “theoretical” P-wave radiation patterns for known source mechanisms;
- For several events, compare the “theoretical” radiation patterns with the patterns obtained from the hydraulic fracturing tests and determine the moment tensor of these AE events (located in white patching zones);
- Determine the most likely source mechanism based on the (1) moment tensor and (2) SEM images captured in the same locations as the AE events analyzed

Source Mechanism of Fracturing Events

Moment Tensor - Assumptions



Aki and Richards (1980)

A mathematical representation of the movement on a crack/fracture; it consists of nine generalized couples, or nine sets of two vectors

The **diagonal terms** are **opening** mechanisms

The **off-diagonal** terms are **sliding** mechanisms

The laboratory hydraulic fracturing tests produce cracks in the 1,2 plane (blue in the left)

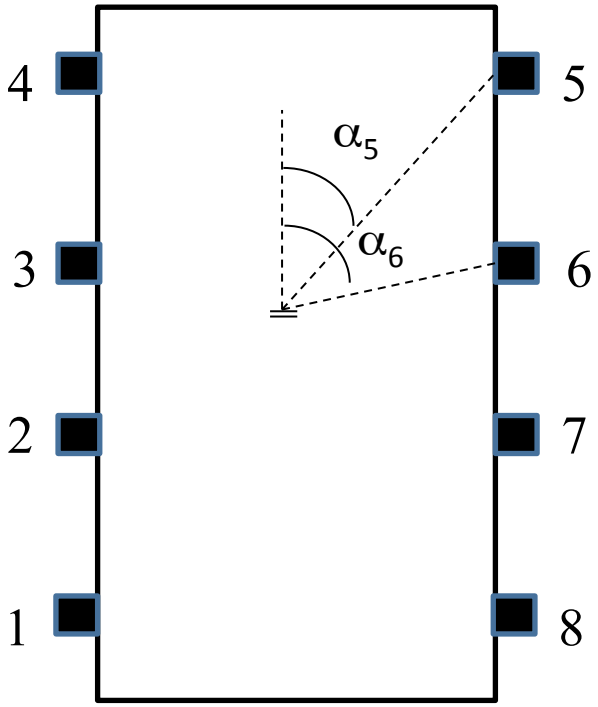
Source Mechanism of Fracturing Events

Comparison between Theoretical and Actual Radiation Patterns

$$A_{Theoretical} \begin{cases} A_{TFP} = (\lambda/\mu + 2\cos^2\alpha) r \end{cases}$$

Theoretical Far-field amplitude of P-waves due to a tensile dislocation

With λ, μ = Lamé Constants



$$Differences = \sum_{i=1}^{8} Abs(A_{i\,Actual} - A_{i\,Theoretical})$$

i = Sensor 1 to 8

A_i^{Actual} = Actual 1st P-wave Amplitude at sensor i

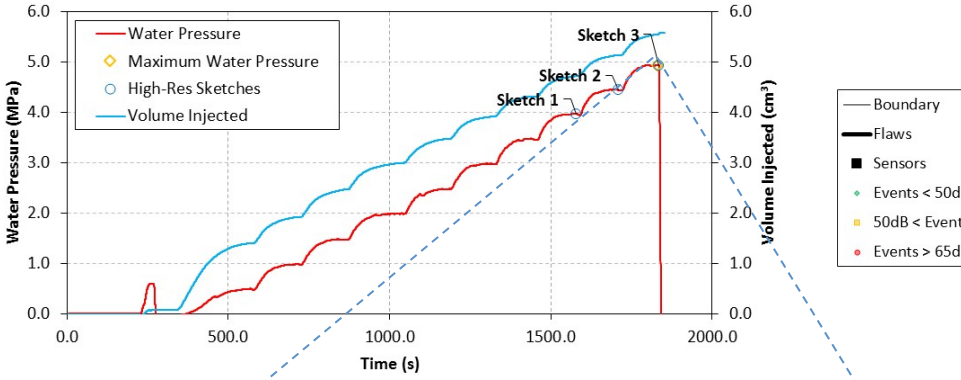
For the different combinations of Theoretical Normalized Amplitudes, obtained by varying the Angle of the infinitesimal principal element and Principal Moments ratios

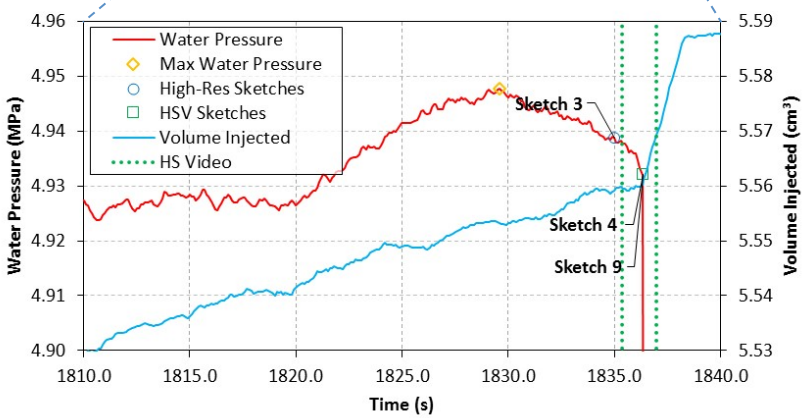
The minimum "difference" combination gives us the most likely moment tensor

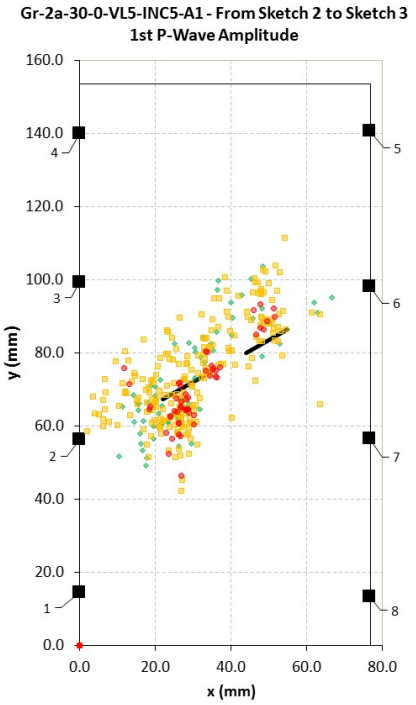
Source Mechanism of Fracturing Events

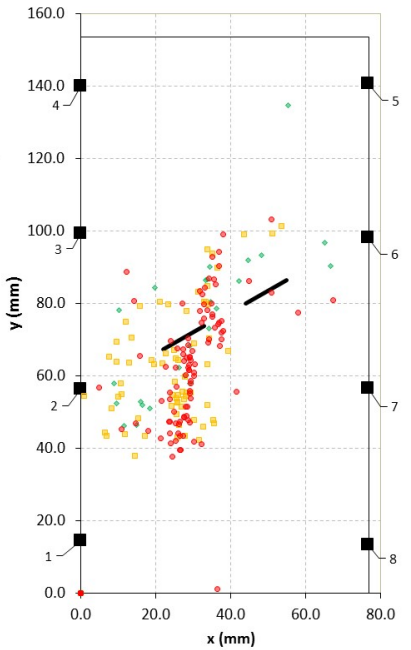
Test studied - Gr-2a-30-0-VL5-INC5-A1

Water Pressure and Volume Injected Vs Time





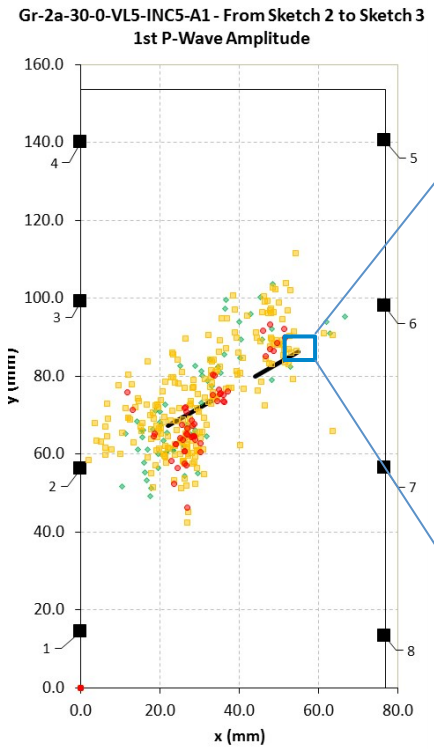




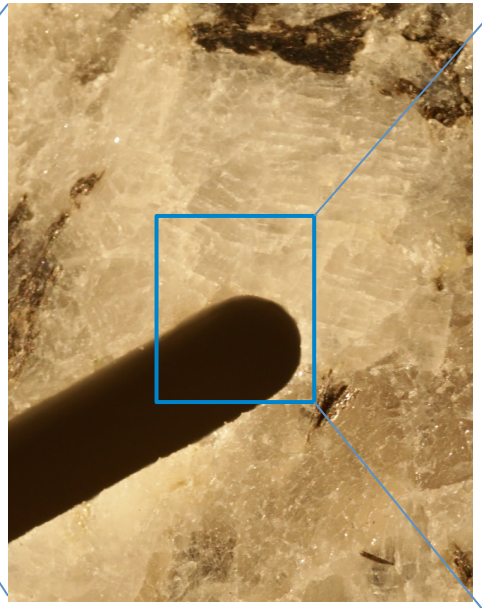
~~From Sketch 2 to Sketch 3~~

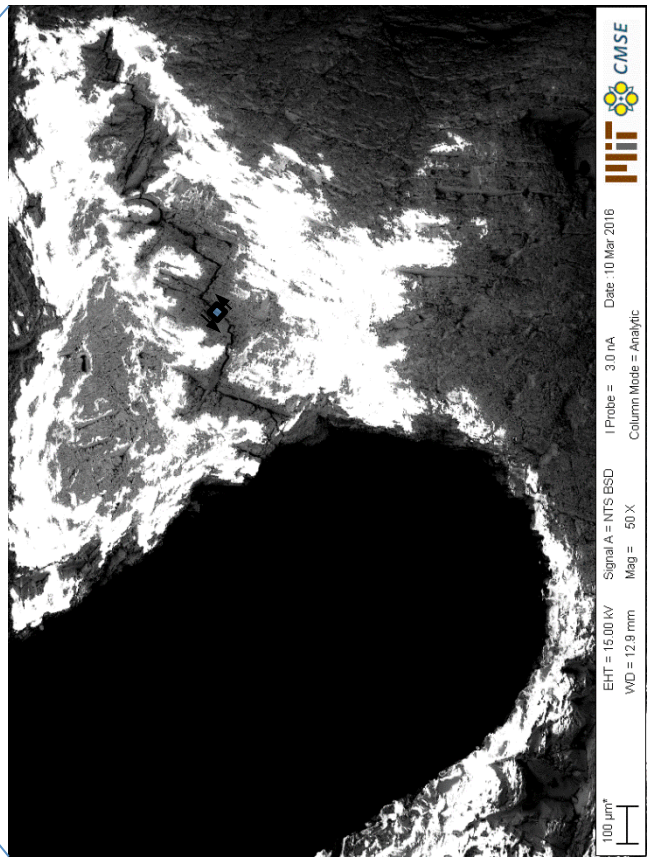
Source Mechanism of Fracturing Events

Test studied - Gr-2a-30-0-VL5-INC5-A1



From Sketch 2 to Sketch 3

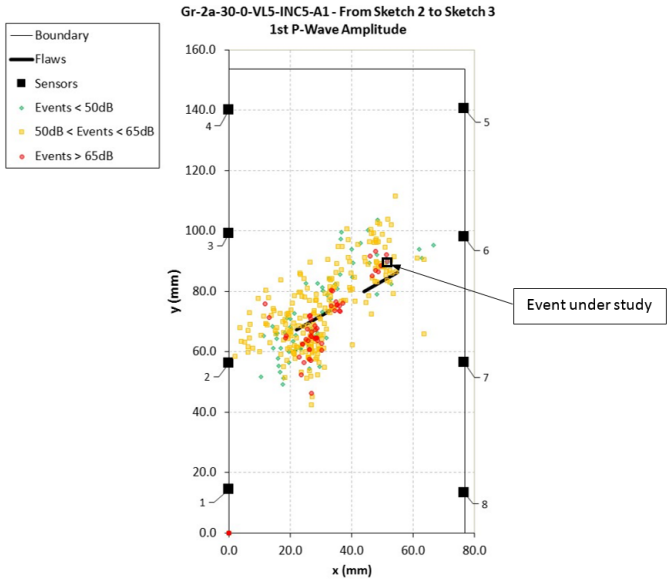


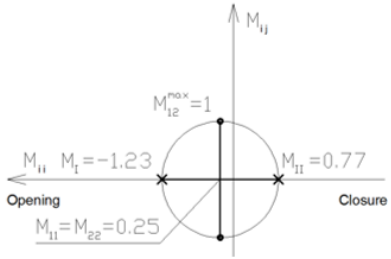


The SEM images indicate that the micro-cracking is responsible for the white-patches

Source Mechanism of Fracturing Events

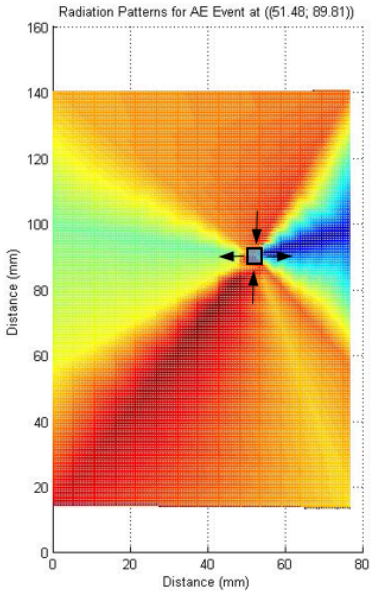
Events at/near Upper Flaw Tip - AE Event at (51.48;89.81)



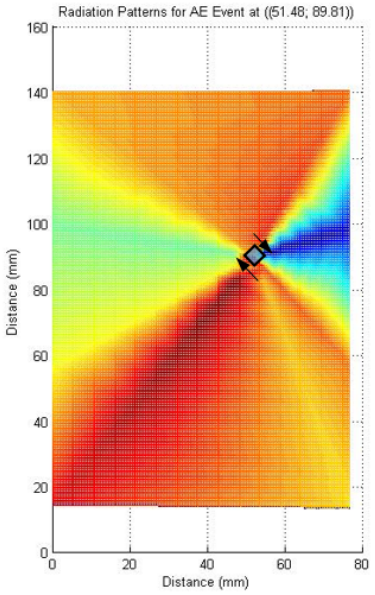


Mohr Circle for the Moment Tensor of the AE event

1) M_I=1.23 and M_{II}=-0.77
2) Or M_{12}^{max}=1 when M_{11} and M_{22} are 0.23



1)

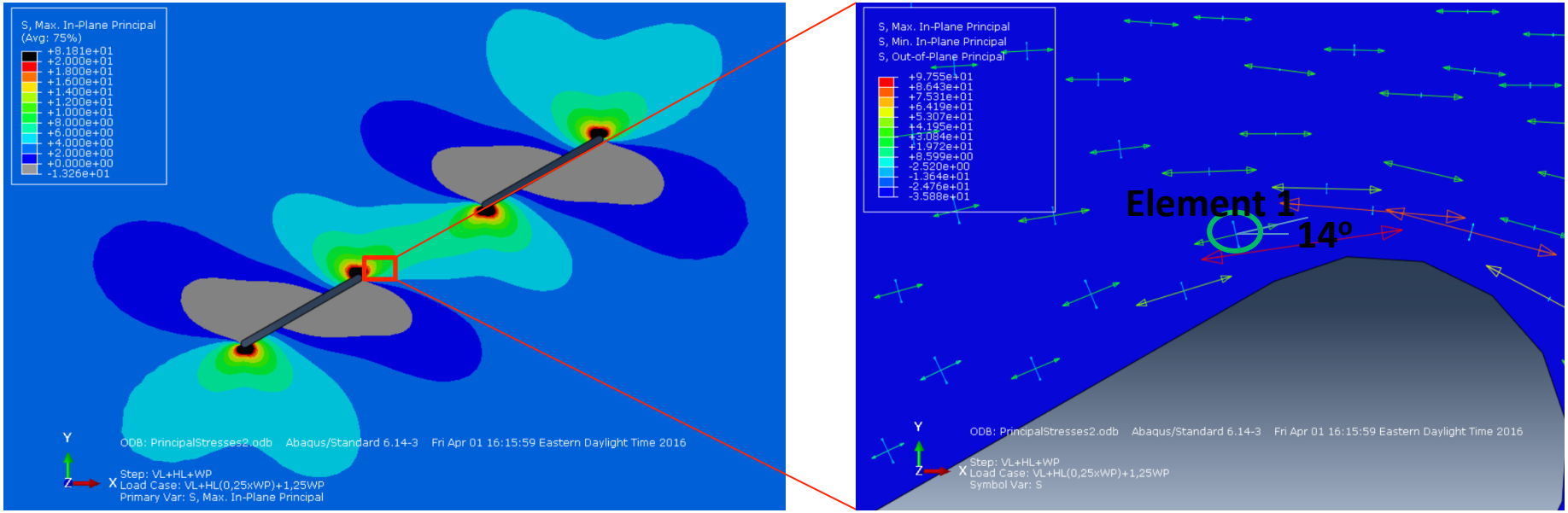


2)

- Source mechanism can be 1), 2) or some linear combination of these two cases
- Need more information (SEM, Finite Element modeling) to identify which case

Source Mechanism of Fracturing Events

Events at/near Upper Flaw Tip – Numerical Analysis

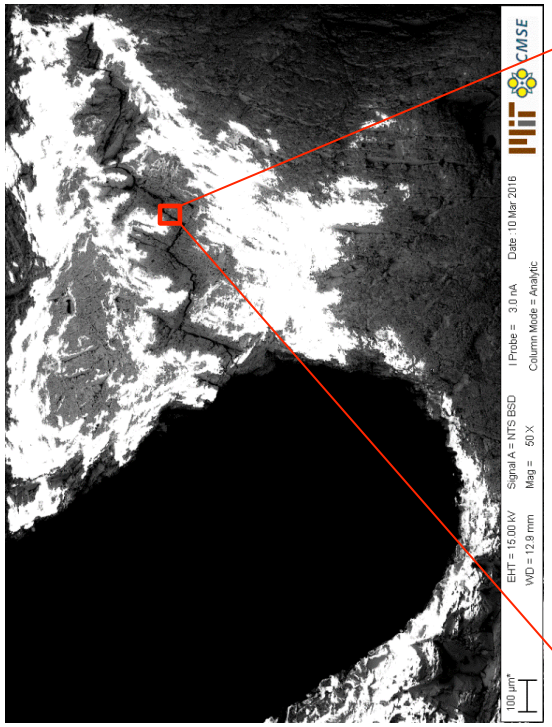


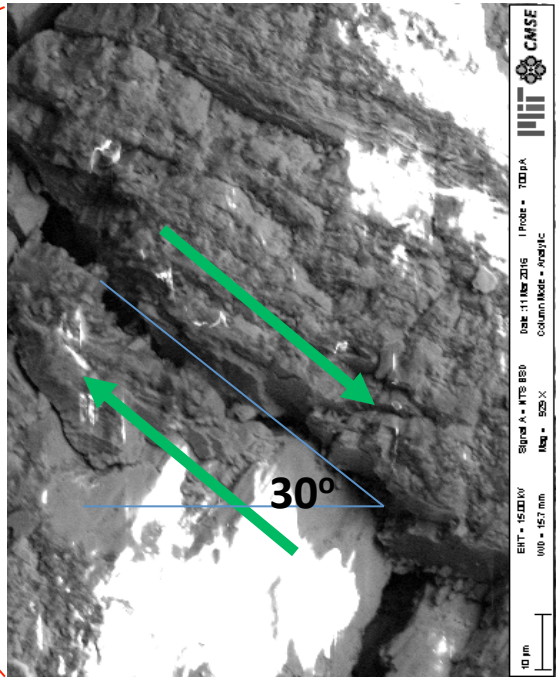
Vertical load = 5.0 (pressure units)
Water Pressure = 6.1 (pressure units)

- Element 1 is located near the place where the AE event under study was captured

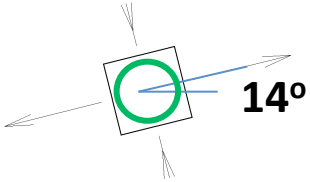
Source Mechanism of Fracturing Events

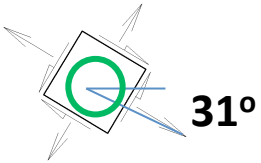
Events at/near Upper Flaw Tip – SEM Analysis





Element 1



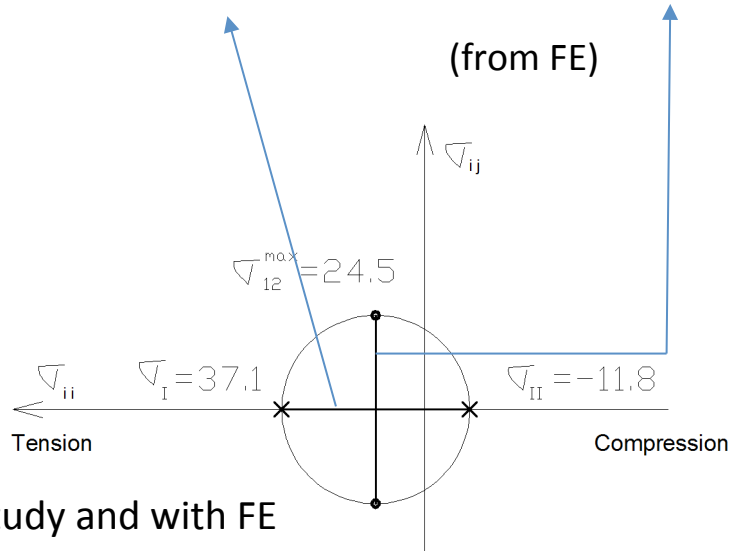


Principal directions

(from FE)

Maximum shear directions

(from FE)



- Comparing SEM with moment tensor from radiation pattern study and with FE analysis, some of the events captured seem to have a strong shear component

Conclusions

- The equipment developed to apply fluid pressure inside the flaws is capable of successfully initiating and propagating hydraulic fractures
- Fracturing patterns for geometries with 0^o- and 30^o-bridging angles are vertical-load-dependent, becoming less dependent as the bridging angle increases
- The water pressure necessary to fracture the specimen is usually higher when the specimen is subject to a vertical load
- The ratio $WP^{(5MPa)}/WP^{(0MPa)}$ seems to decrease as the bridging angle increases
- Moment tensor of AE events studied near the upper flaw tip where white-patching occurred + the SEM images captured in the same region indicate that the events have a strong shear component
- The source mechanisms obtained from the radiation patterns are consistent with the Finite Element analysis and SEM observations